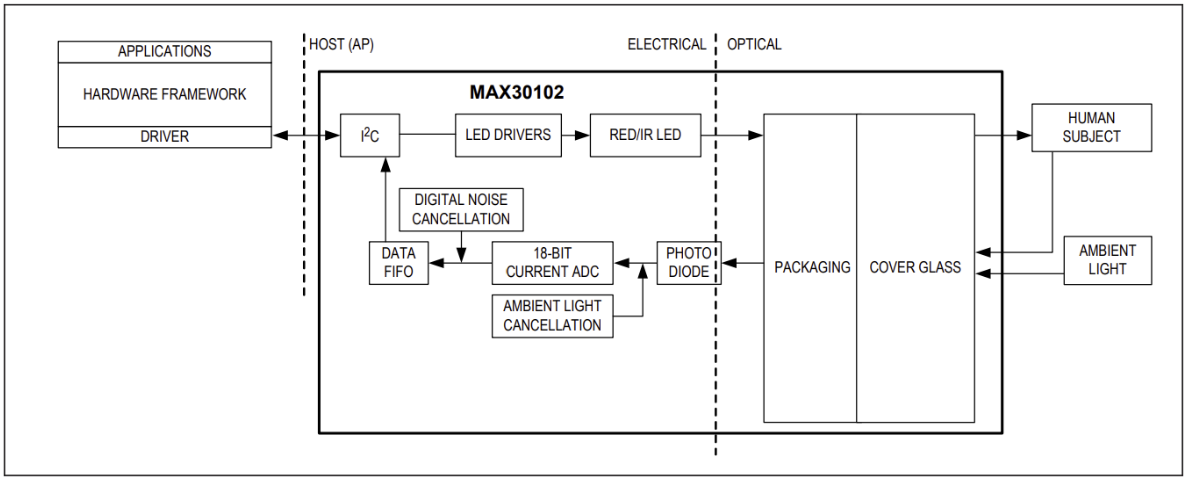
The Role of DSP in the MAX30102

System Diagram

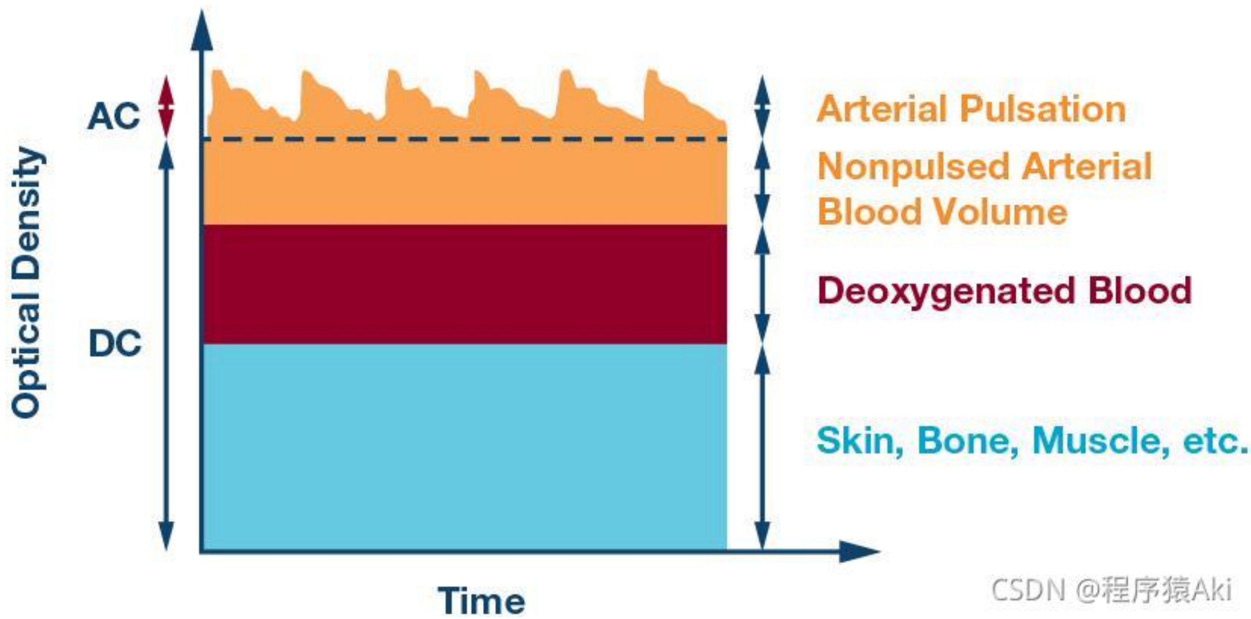


MAX30102 Sensor:

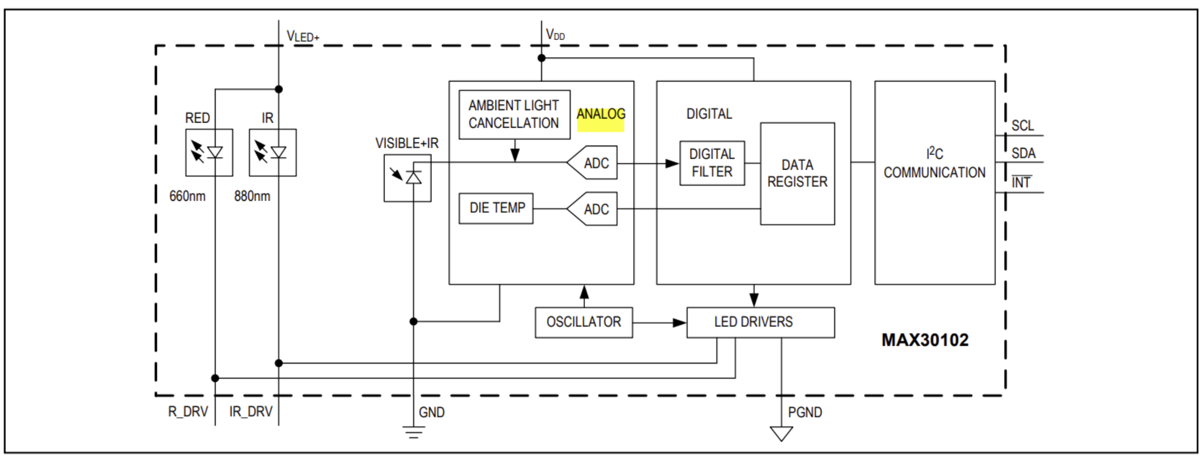
- I2C Interface: Used for data transfer between the host and the sensor.
- LED Drivers: Control the emission of the red and infrared LEDs.
- Red/IR LEDs: Emit red and infrared light to detect heart rate and blood oxygen saturation.
- Photodiode: Detects the light signals reflected from human tissue.
- 18-Bit ADC: Converts the analog signals received by the photodiode into digital signals.
- Ambient Light Cancellation: Eliminates interference from ambient light.
- Digital Noise Cancellation: Reduces noise in the signal.
- Data FIFO: Buffers sensor data before transmitting it to the host.

Photoplethysmogram (PPG)

A PPG signal is generated when light is shone on the skin, and blood flow causes variations in light absorption. Other tissues (like bones and muscles) have relatively constant light absorption rates. Thus, the light reflection varies with blood flow. The DC signal reflects tissues, bones, muscles, and veins, while the AC signal reflects arterial blood flow. By analyzing the AC and DC signals, heart rate and blood oxygen levels can be calculated.



Functional Diagram

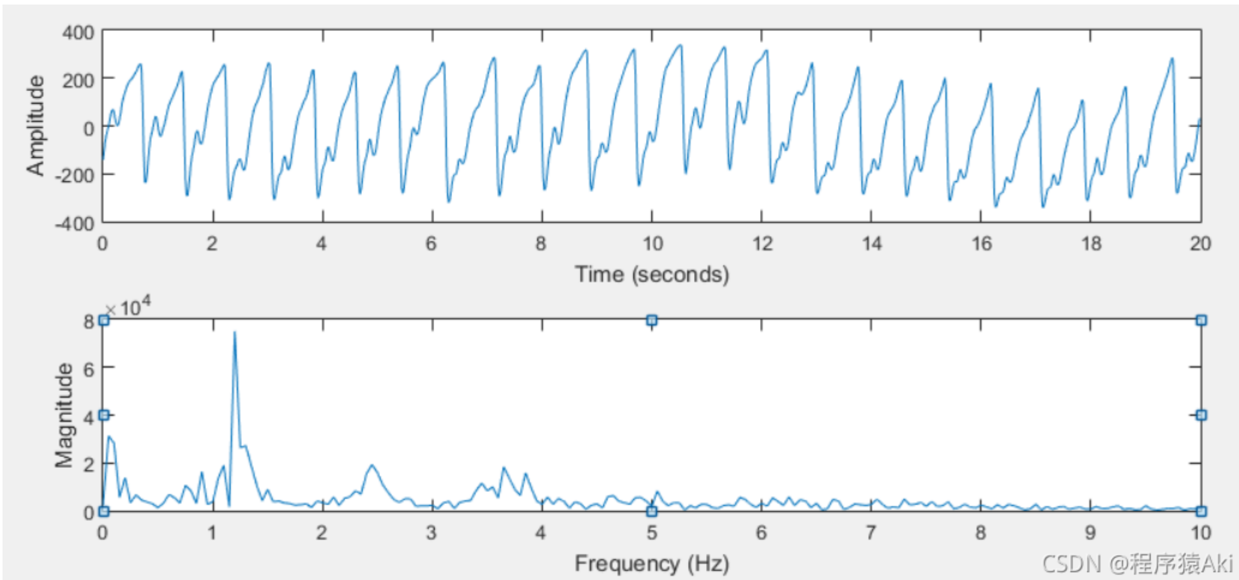


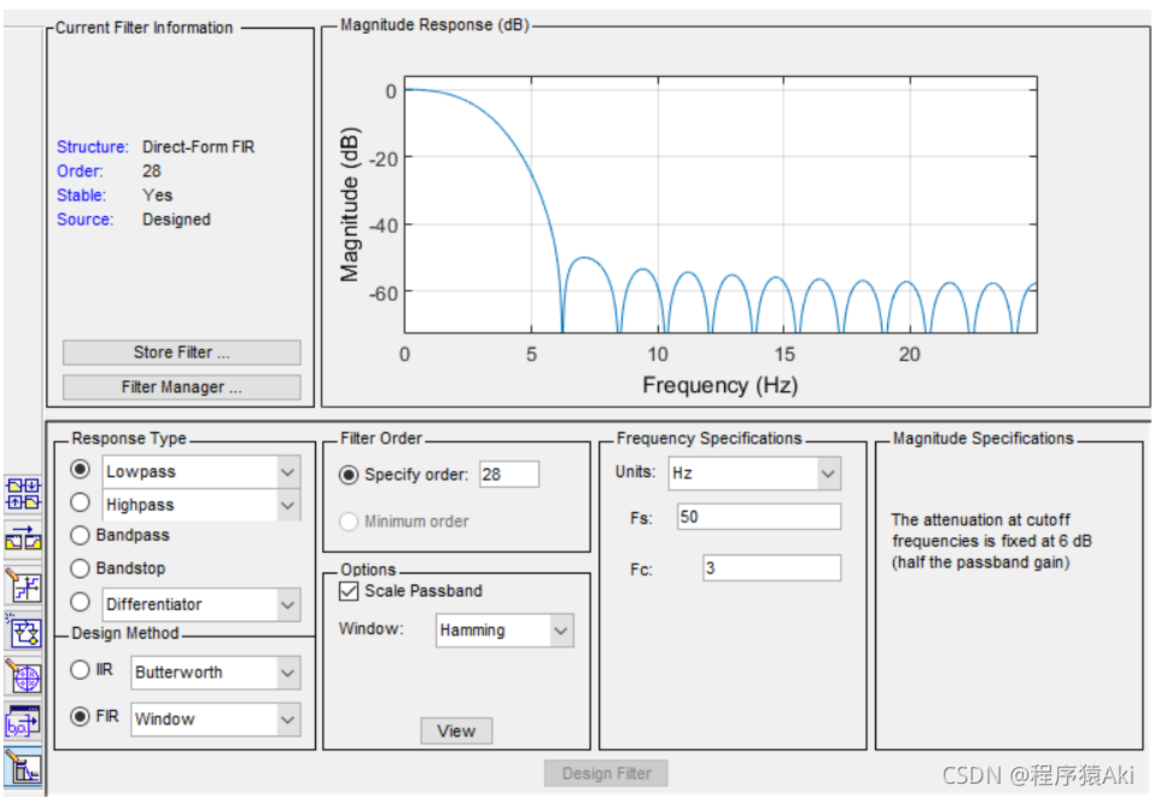
MAX30102 Components:

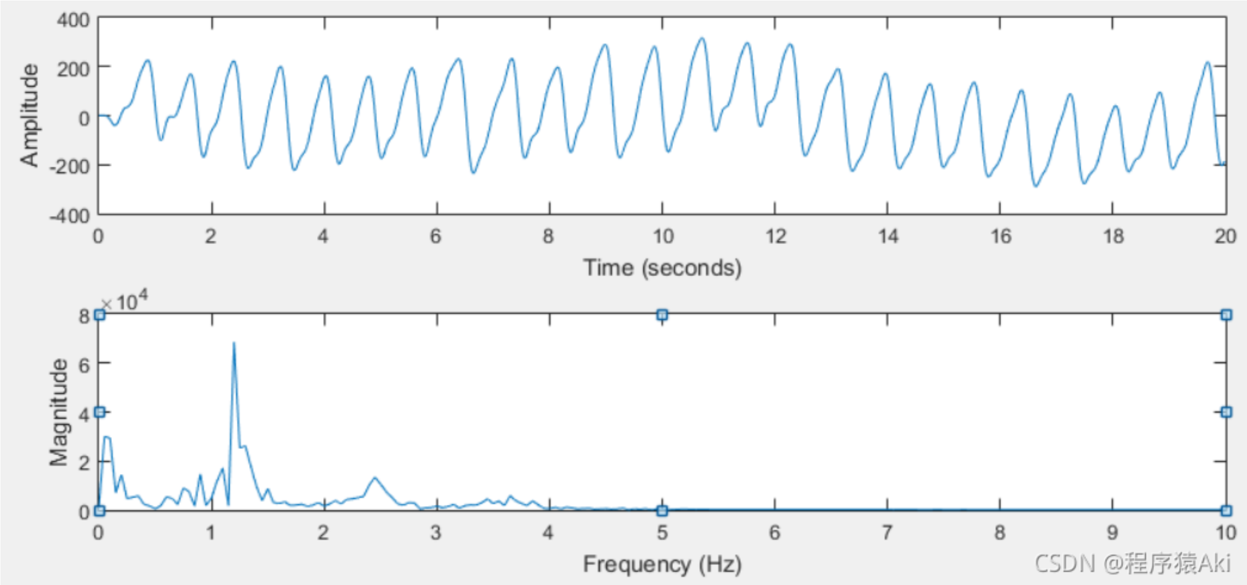
1. Light Sources: Includes red and infrared LEDs.
2. Photodetector: Detects light signals reflected or transmitted through tissue.
3. Analog Front End (AFE): Includes amplifiers and filters for initial signal processing.
4. ADC: Converts analog signals to digital.
5. DSP: Further processes and analyzes the signal.

FIR Filter

The frequency components of the PPG signal mainly concentrate between 0.5-2 Hz. To eliminate individual differences, frequencies between 0.5-3 Hz should be retained. A low-pass filter designed using Matlab's FDA Tool keeps frequencies below 3 Hz while filtering out higher frequencies.







Heart Rate Calculation

Time Domain Method: The interval between two points on the PPG waveform passing the dynamic threshold curve is considered one period of the PPG signal. Heart rate can be calculated based on this period. The value at a certain point on the dynamic threshold curve is the average of points over several previous periods.

Algorithm Logic:

1. Threshold detection: Start heart rate calculation only when the threshold (sensor close to the skin) is reached.

2. Wait for the waveform to stabilize: Discard the initial unstable data when the skin first contacts the sensor.

3. FIR filtering and storing in a buffer: The buffer stores data points from several previous periods to determine the current threshold value.

4. Detect PPG signal crossing the threshold curve.

5. Heart rate calculation: Use the MCU's timer to increment time in milliseconds when interrupted, starting calculation from zero.

Blood Oxygen Saturation

Principle: The MAX30102 sensor has red (660nm) and infrared (880nm) LEDs. The absorption rates of oxygenated and deoxygenated hemoglobin differ at these wavelengths. SpO2 (blood oxygen saturation) is calculated using the ratio \(R \) in a formula where a, b, and c are experimentally determined constants. This ratio compares the AC and DC components of red and infrared light.

SpO_2 measurement is achieved by the following equation:

$$\mathrm{SpO_2} = aR^2 + bR + c$$

where R is determined by the following equation:

$$\mathrm{R} = \frac{\mathrm{AC_{red}}/\mathrm{DC_{red}}}{\mathrm{AC_{ired}}/\mathrm{DC_{ired}}}$$

Reference:

MAX30102 脉搏血氧仪和心率传感器（一）驱动程序_stm32 驱动 max30100-CSDN 博客

MAX30102 脉搏血氧仪和心率传感器（二）FIR 滤波器_脉搏波 fir 滤波器设计-CSDN 博客

MAX30102 脉搏血氧仪和心率传感器（三）心率计算——时域法_max30102 心率算法详解-CSDN 博客

MAX30102 脉搏血氧仪和心率传感器（四）血氧+心率完整版（STM32）_max30102 血氧检测 csdn-CSDN 博客

MAX30102--High-Sensitivity Pulse Oximeter and Heart-Rate Sensor for Wearable Health (analog.com)

Artifacts

Artifacts exist in both medical imaging and general signal processing. In these fields, artifacts mean interference, noise, or errors that are not the desired signal, affecting the accuracy of measurements.

Types of Artifacts:

- **Ambient Light Interference:** Caused by external light sources like sunlight or indoor lighting, interfering with the sensor's measurements.
- **Motion Artifacts:** Result from relative movement between the sensor and the skin, causing sudden changes in sensor readings and leading to inaccurate heart rate or blood oxygen measurements.

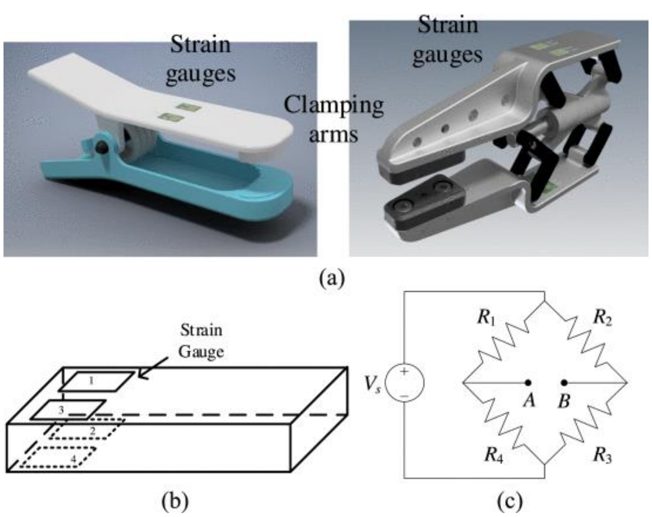
- **Electrical Noise:** Electromagnetic interference from many devices can affect the sensor's electronic circuits, resulting in erroneous signal readings.
- **Physiological Artifacts:** Caused by other physiological activities such as breathing, muscle contractions, and changes in blood flow, influencing the sensor's readings (specific to medical sensors).

Solutions to Artifacts

Hardware Method: Strain Gauge-Based Motion Artifact Sensor

Motion artifacts are interference signals caused by voluntary or involuntary movements during measurement. These signals overlap with the measured signal, leading to errors and signal misinterpretation. Since body movements are unpredictable, it's hard to avoid these artifacts completely. Common solutions include statistical analysis, adaptive filtering, and signal processing techniques, or mechanical adjustments for correction. If the raw data is corrupted by artifacts, the original signal is usually irrecoverable. Thus, a better strategy is to actively control motion and detect artifacts during data acquisition. To address relative movement between the measurement site and the measurement system, a strain gauge is used as a new motion artifact sensor.

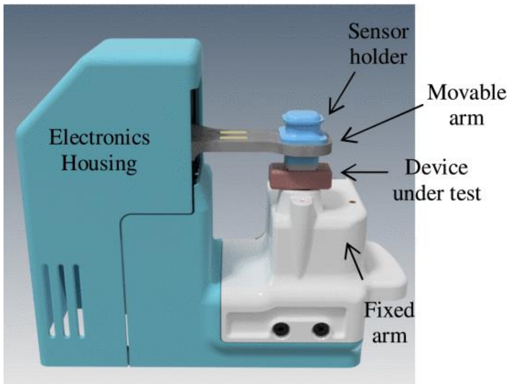
This model includes two arms clamped to the measurement site, with four strain gauges on one arm forming a full bridge circuit. When motion artifacts occur, the cantilever deforms, and the strain gauges sense this deformation, producing a voltage change proportional to the strain. During measurement, the two arms are clamped to the measurement site; if the site moves relative to the system, motion artifacts are generated.



(a) Proposed Model of Motion Artifact Sensor (b) Strain Gauge Arrangement on One Arm

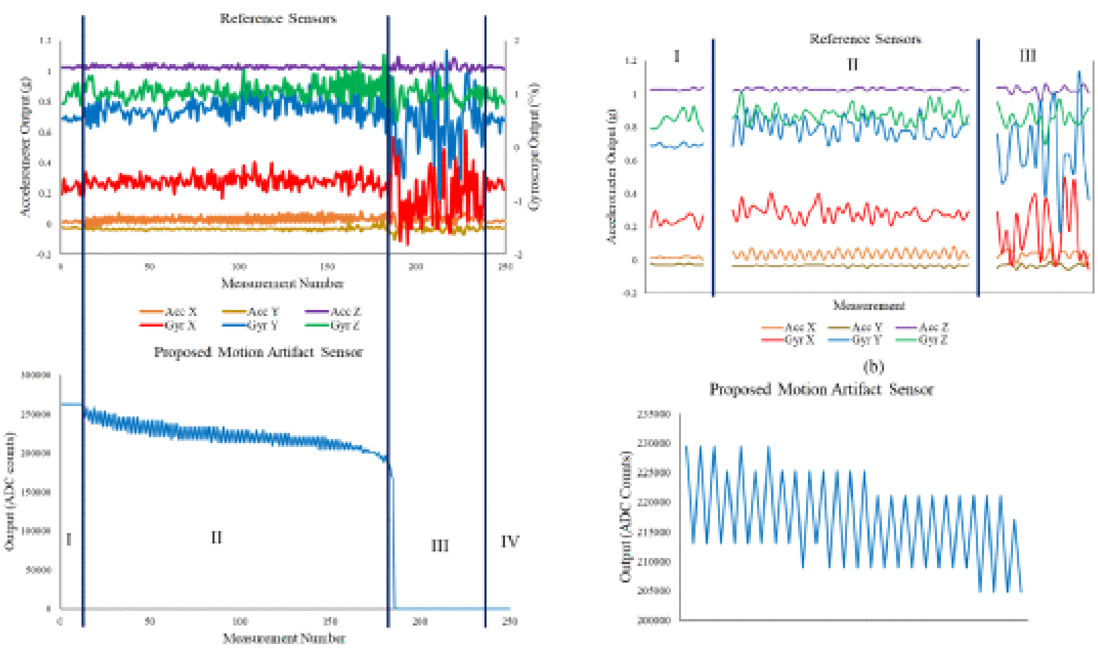
(c) Equivalent Electrical Model of Arrangement in (b)

The motion artifact sensor consists of a fixed arm and a movable arm, the latter acting as a cantilever beam with strain gauges directly placed at the sensor's stress points to accurately record deformations proportional to the input force. The device is mounted on an aluminum base plate for stability, protecting the system from external movements like shaking and vibrations.

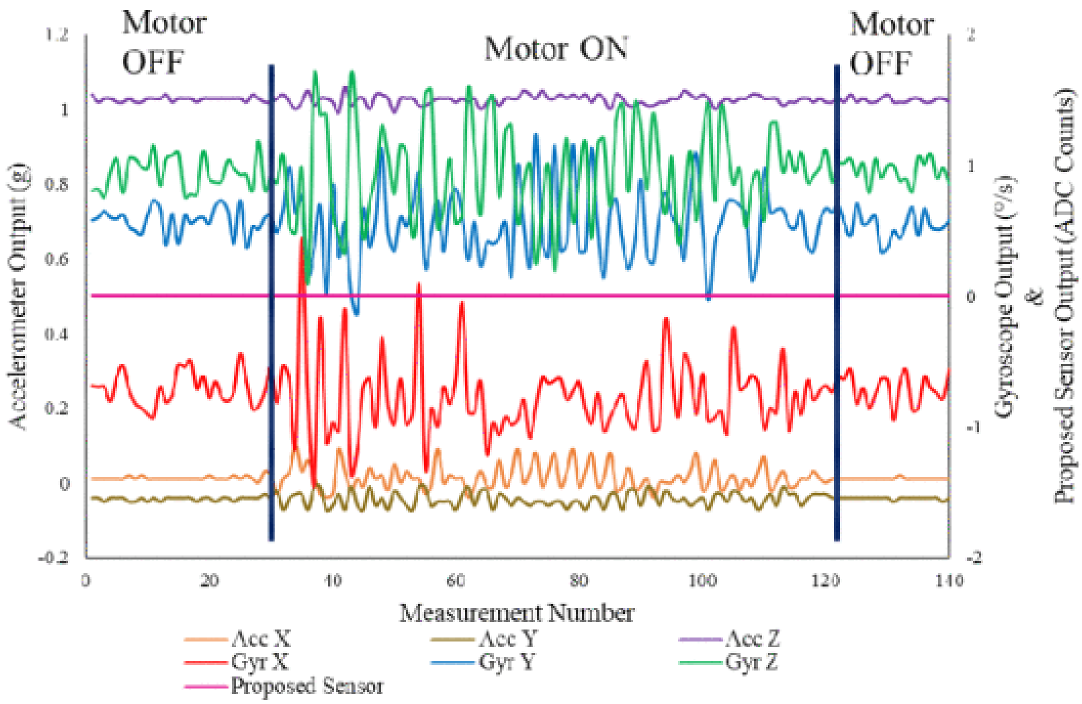


Experiment:

A device with oscillating components and a vibrating motor simulated motion artifacts to validate the strain gauge-based sensor's effectiveness. Initially, the oscillating component driven by a stepper motor detected motion artifacts when clamped by the sensor. Results showed that the proposed sensor accurately detected motion artifacts during different oscillation stages, unlike traditional accelerometers and gyroscopes, which were heavily influenced by external noise. Additionally, the vibrating motor experiment demonstrated that while traditional sensors responded significantly to motor operation, the proposed sensor did not, indicating its insensitivity to external interference and effectiveness in detecting motion artifacts.



(a)
(b)
(c)



The graph shows measurements over time, with the horizontal axis representing measurement times and the vertical axis showing outputs from the accelerometer (Acc), gyroscope (Gyr), and the proposed sensor. When the motor is off, all sensors show stable outputs. When the motor is on, traditional sensors display significant fluctuations due to motor vibrations, whereas the proposed strain gauge sensor remains stable and unaffected. Upon turning the motor off again, traditional sensors return to stability, and the proposed sensor continues to show consistent stability. This data indicates the proposed sensor's superior stability and reliability under external vibration interference, effectively detecting motion artifacts without noise influence.

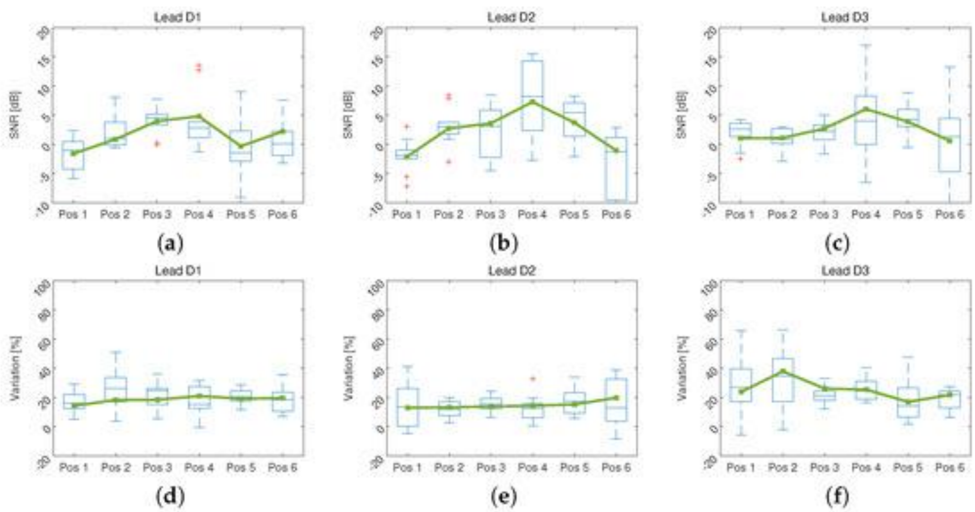
Reference: [Motion Artifact Sensor Using Strain Gauges | IEEE Journals & Magazine | IEEE Xplore]

Hardware Method: Electrode Position Optimization

Artifacts in ECG monitoring are primarily caused by improper electrode placement and patient movement. These artifacts can lead to signal distortion and affect diagnostic accuracy. By optimizing electrode positions and using advanced algorithms, the impact of artifacts can be reduced. Using computational models to determine the optimal electrode placement and employing wearable devices for measurement can help minimize artifacts and improve monitoring accuracy.

This study proposes a model to compare ECG signals obtained from different positions on the volunteer's torso and to adjust ECG signals from non-traditional positions to standard positions (as defined by the Einthoven triangle). The study also examines the effect of these position changes and motion artifacts on the distortion of ECG signal waveforms. To measure the changes in ECG signals caused by motion artifacts and their relation to electrode position, the study uses Signal-to-Noise Ratio (SNR) to quantitatively calculate the differences between test signals and reference signals, both affected by motion artifacts.

The study analyzes the SNR of signals contaminated by motion artifacts at different positions and compares them to signals from standard positions to evaluate the effectiveness of electrode position optimization in reducing artifact impact. The figures show SNR measurements and Dynamic Time Warping (DTW) results for ECG signals obtained from different torso positions. By comparing signals from volunteers at different positions and under different motion states, the study determines the extent of signal changes caused by artifacts. These analyses help understand the impact of electrode position changes on artifacts and optimize ECG signal acquisition locations to minimize artifact influence on signal quality.



(a), (b), and (c) show the SNR of ECG signals obtained from different positions, with the green line representing the median SNR and the box plot showing the data distribution range. (a) Shows that Lead D1 has higher SNR at positions Pos 3 and Pos 4, indicating better signal quality at these locations. (b) Shows that Lead D2 has higher SNR at positions Pos 4 and Pos 5. (c) Shows that Lead D3 has higher SNR at position Pos 4, suggesting it is a better position.

(d), (e), and (f) show the signal change evaluation using the DTW method, with the green line representing the median signal change. (d) Shows that Lead D1 has smaller signal changes at positions Pos 3 and Pos 4, indicating less artifact impact. (e) Shows that Lead D2 has smaller signal changes at positions Pos 4 and Pos 5. (f) Shows that Lead D3 has smaller signal changes at position Pos 4, suggesting it is a better position. From this data, it can be seen that Pos 4 shows better signal quality and smaller artifact impact across all leads, indicating it can be optimized as the best placement position for ECG electrodes to reduce artifact influence on the signal.

Motion artifacts cause signal distortion and affect diagnostic accuracy. While changing electrode positions can reduce artifacts, the effectiveness of this method can vary due to individual differences. The study uses SNR and DTW methods to evaluate the impact of artifacts at different electrode positions, showing that merely moving the electrode positions may not significantly improve signal quality. Therefore, a computational model is needed to optimize electrode positions, especially considering the impact of volume conductor changes on the signal. This approach can reduce artifacts and improve the accuracy and diagnostic reliability of wearable ECG devices.

Reference: Sensors | Free Full-Text | Sensitivity and Adjustment Model of Electrocardiographic Signal Distortion Based on the Electrodes' Location and Motion Artifacts Reduction for Wearable Monitoring Applications (mdpi.com)